

EVAPORATION AND EVAPORATORS

David P. Kessler

Purdue University, West Lafayette, Indiana, U.S.A.

INTRODUCTION

In the general sense, *evaporation* refers to any change in phase of a component from liquid to gas. *Vaporization*, sometimes used interchangeably with *evaporation*, is at times specifically used to designate the total change of a liquid phase to gas (vapor).

In this article only the term *evaporation* will be used. Evaporation will be defined as processes carried out in process equipment conventionally classified as *evaporators*. This, in turn, implies that nonequipment-contained classes of evaporation, such as solar ponds and oil tanker spills, will be ignored.

Evaporators are used to increase the concentration of relatively nonvolatile dissolved or suspended components in a solution or slurry (the *liquor*) by evaporating portions of the liquid phase using energy supplied by a *medium*, often steam. The dissolved or suspended components do not appear in the vapor phase to a substantial extent. (If they do, the process is referred to as *distillation*.)

Other methods that will not be discussed here, but also can be used to increase concentration (some with and some without concomitant evaporation) are reverse osmosis, ion exchange, dialysis, electrodialysis, osmotic distillation, and applications that involve fluidized beds, cooling towers, or evaporation of aerosols.

In most evaporators, the solvent or suspending phase is primarily or totally one constituent, most frequently water. The important product in evaporation can be either the more concentrated mixture left behind or the overhead vapor (which is often, but not necessarily, subsequently condensed).

The overhead solvent vapor in solvent recovery processes or boiler water vapor in power plant applications typifies vapor products. *Blowdown* refers to the periodic or continuous purging of the bottoms used to control buildup of undesirable material in the liquid phase when producing a vapor product (1).

Some processes of evaporation can be accompanied by crystallization, as the residual liquor grows more and more concentrated. Carried yet further, evaporation evolves to *drying* (or dehydration, if the constituent removed is

water), as the bottoms product obtained becomes primarily solid rather than liquid.

TYPICAL APPLICATIONS FOR EVAPORATORS

Historically, a classic example of an evaporation process is the production of table salt. Maple syrup has traditionally been produced by evaporation of sap. Concentration of black liquor from pulp and paper processing constitutes a large-volume present application. Evaporators are also employed in such disparate uses as: desalination of seawater, nuclear fuel reprocessing (1), radioactive waste treatment (2, 3), preparation of boiler feed waters, and production of sodium hydroxide (2). They are used to concentrate stillage waste in fermentation processes, waste brines, inorganic salts in fertilizer production, and rinse liquids used in metal finishing, as well as in the production of sugar, vitamin C, caustic soda, dyes, and juice concentrates, and for solvent recovery in pharmaceutical processes.

TYPES OF EVAPORATORS

Extended discussion of types (including photographs and schematic diagrams), design, and operation of evaporators can be found in the literature (4–6).

Because evaporation of a liquid phase usually requires addition of large amounts of thermal energy, the method of transferring this heat to the liquor tends to dominate evaporator capital cost. The source of heat for evaporators is usually a medium such as hot combustion gases or a condensing vapor, typically steam. Molten salts and electrical resistance heaters are less commonly used sources of thermal energy.

Flash evaporators operate by an adiabatic decrease of the pressure on a liquid that has been previously heated. These were first used for production of potable water on ships; now they are used for more general brackish waters and seawater as well as for processed liquids (7).

Disk or *cascade* evaporators use the partial immersion of either disks mounted perpendicular to, or bars mounted parallel to a rotating shaft to carry films of liquid into a hot gas stream (8).

The most efficient method of transferring the energy of a heating medium to the liquor is direct injection of the heating medium. Because of the consequent contamination of the liquor with the heating medium, this method of heat transfer is of relatively less importance in the pharmaceutical industry and will not be discussed here.

The more useful methods for pharmaceutical products maintain purity at the expense of additional resistance to heat transfer by interposing a solid wall of some thermally conductive material between the heating medium and the liquor. The solid wall is usually metallic, but can be coated with materials such as glass, porcelain enamel, or polymers. Glass or ceramic themselves can be used for walls.

The solid wall can be the wall of the evaporator itself, as in *jacketed* evaporators. The area available for heat transfer in jacketed vessels, however, is quite limited. Jacketed vessels frequently incorporate some sort of internal agitator.

Heat transfer can be supplied from within a vessel by a heating coil, but again, the available heat transfer area is not large; however, such coils can be designed in ways that

make their removal for cleaning relatively easy. The alternative is to have the heat exchange external to the main chamber of the evaporator.

Some applications use plate-type exchangers. In plate exchangers, the bounding surface may be in the plate-and-frame form (parallel plates with the heating medium and the liquor flowing in alternate interstitial spaces), or in a spiral-plate configuration that contains a concentric pair of spiral passages (7). Such exchangers can be cleaned easily. They do, however, require a large gasketed area. Fig. 1 shows a typical plate-type evaporator.

The most common geometry for the separating surface between the heating medium and the liquor is probably that of tube bundles, which can be oriented either horizontally or vertically, with the liquor flowing on either the outside or the inside of the tubes. Depending on the application, the tube bundle can be either inside or outside the vessel in which the evaporation takes place.

The heating element of an evaporator is sometimes referred to as a *calandria*. Usually this term is applied to a heating system in which the liquor rises through a vertical tube bundle surrounded by the heating medium and then descends through a central well.

The *short-tube vertical* evaporator is an early type that still sees considerable industrial use. The heating element,

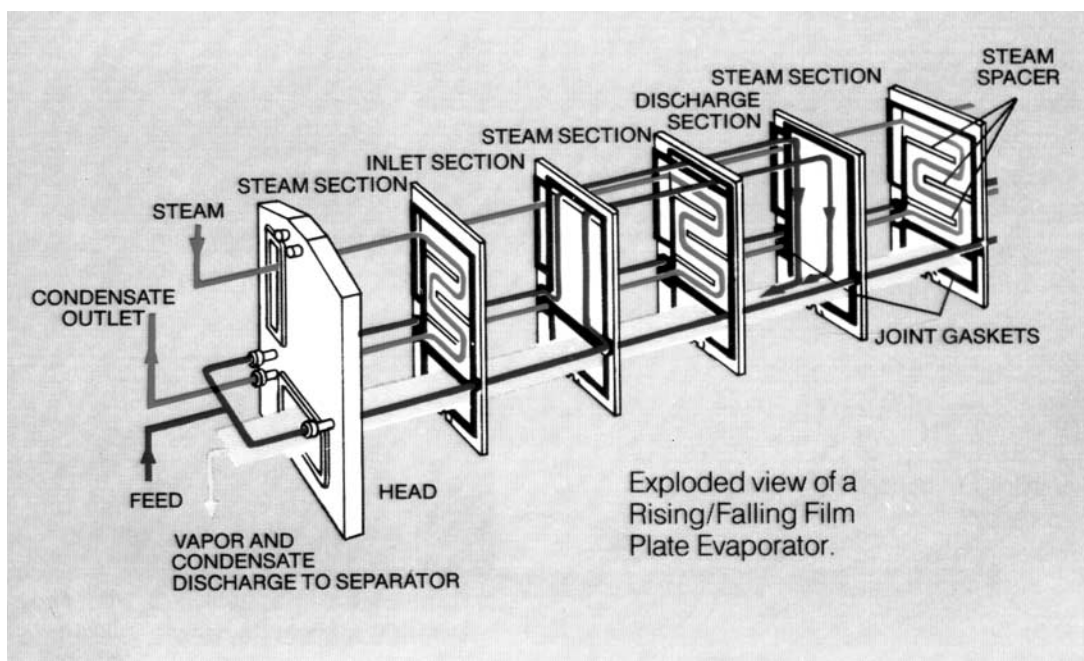


Fig. 1 Exploded view of rising/falling film plate evaporator. (Courtesy of APV Crepaco, Inc., APV Americas, Rosemont, IL—An Invensys Company.)

a vertical bundle of tubes around a center well, is sometimes colloquially referred to as the basket. Circulation is upward through the tubes, the *rising film* mode, and then downward through the central well or *downtake*. Liquid boils in the tubes, which decreases the overall density therein and thus creates the driving force for circulation, since the density of the (nonboiling) fluid in the downtake is greater than that in the tubes.

Mechanical cleaning is fairly easy with such units, and the capital investment is relatively low. Circulation stops, however, if the heat input is interrupted, creating the danger of the settling of any solids suspended in the liquor. This type of unit is not well suited to viscous liquids because of the low heat transfer coefficients associated with the low velocities of natural convection (8). Short-tube vertical evaporators have largely been surpassed by other types, particularly for applications involving liquors that foam, deposit excessive scale, are excessively viscous, or are heat sensitive.

Long-tube vertical evaporators are normally the cheapest per unit of capacity (8). When operated in the rising film mode, temperature variation along the inside of the tubes is both substantial and difficult to predict. The variation in pressure from high at the bottom to low at the top normally means that the liquid enters the bottom of the tubes below its boiling temperature. The liquid is subsequently heated to boiling as it rises, and the boiling temperature simultaneously decreases as the pressure decreases toward the top of the tube (assuming any boiling point rise from increasing concentration is overshadowed by the effect of the reduced pressure on the boiling point).

By operating a long-tube evaporator in the *falling film* mode, the problem of temperature variation induced by pressure differences is mitigated. Here, a film of liquid surrounding a gas core flows down the walls of the tube, so pressure drop is very much less than in the rising film mode. The low residence time of the falling film units makes them useful for heat-sensitive materials, but the necessity of maintaining a film on the walls of the tubes makes feed distribution a problem. They are readily adapted to sanitary processing. Evaporators that combine rising film sections and falling film sections in the same unit are also available.

Forced circulation evaporators have relatively higher heat transfer coefficients, and are somewhat less subject to fouling, salting, and scaling. This advantage is offset by both the cost of external power required for the circulating machinery and a relatively high holdup (8). At times they more frequently experience plugging from deposits detached from the walls of the unit by the force of the circulating fluid. The introduction of a pump may lead to mechanical problems, particularly with liquors that are slurries.

Liquor velocities required to prevent surface deposits are often greater than can be obtained with natural circulation at reasonably low temperature differences (9). In addition to mitigating scale formation, forced circulation also improves the heat transfer coefficient.

For viscous liquids, one way to increase the heat transferred is to improve the heat transfer coefficient by scraping or stirring the fluid adjacent to the wall, as in *agitated film* or *wiped film* evaporators. Accommodation of the mechanical devices used to mix the fluid close to the wall requires a fairly large diameter tube, so these devices tend to consist of only a single tube; thus, heat transfer area is relatively small. The introduction of moving mechanical parts may lead to maintenance problems.

In *horizontal tube* evaporators, the liquor is usually on the outside of the tubes and the heating medium on the inside. Rather than submerging the tubes, the boiling liquid is sometimes sprayed on the outside of the tubes. This gives a performance approaching that of falling film evaporators (8).

Evaporators can be operated at a variety of pressures (9). Reduced pressure, with its concomitant reduction in boiling temperature, offers advantages for heat-sensitive materials and materials that are sensitive to exposure to air.

Evaporation operations are often staged in *multiple effect* systems (1) to achieve better efficiency. Such systems can have a variety of relative directions for flow of liquor and vapor. A typical example of such staging is illustrated in Figs. 2 and 3.

Detailed discussion of the advantages and disadvantages of various types of evaporators is available (8). A table summarizing the advantages and disadvantages of common types of evaporators also is available (10).

Since most evaporators are purchased from outside suppliers either prefabricated or on-site-fabricated, such suppliers can be an excellent source of information on selection of evaporator type. Suppliers and addresses can be found in the literature (11, 12).

DESIGN OF EVAPORATORS

A number of publications have addressed the design of evaporators at both the elementary and complex levels (1, 2, 7–9, 13–18). The reader is referred to these and to their bibliographies for details.

Efficiency of steam-heated evaporators is commonly described in terms of steam economy, defined as the pounds of solvent evaporated per pound of steam consumed (7).



Fig. 2 Two-effect rising/falling film plate evaporator. (Courtesy of APV Crepaco, Inc., APV Americas, Rosemont, IL—An Invensys Company.)

Important to the design of evaporators is the concept of boiling point rise. Boiling point rise, which normally accompanies increasing concentration in a liquor, is defined as the difference between the boiling temperature of the liquor and that of pure water at the same pressure.

A plot of the boiling point of pure water on the abscissa versus the boiling point of the liquor on the ordinate, with lines of constant concentration plotted as a parameter, is known as a Dühring plot. A Dühring plot is unique to the particular chemical species. A monograph summarizing the boiling point rise for a number of inorganic salts, is available (19), as well as information on general equations to predict boiling point rise either empirically or from other thermodynamic properties (9).

During batch operation, the composition of the liquor in the evaporator is continuously changing. For batch

operation in the absence of significant potential and kinetic energy changes, an energy balance on the system constituted by the liquor in the evaporator shows that the sum of the rate of enthalpy removed in the overhead stream and the change in internal energy of the liquor in the evaporator must equal the rate of energy addition as heat:

$$\hat{H}_{ov}\dot{W} + \frac{d(\hat{U}M)}{dt} = \dot{Q} \quad (1)$$

where

\hat{H}_{ov}	enthalpy of overhead vapor (energy/mass)
\dot{W}	mass flow rate of overhead vapor (mass/time)
\hat{U}	internal energy of liquor (energy/mass)
M	mass of liquor (mass)
\dot{Q}	rate of heat input (energy/time)
t	time (time)
()	units

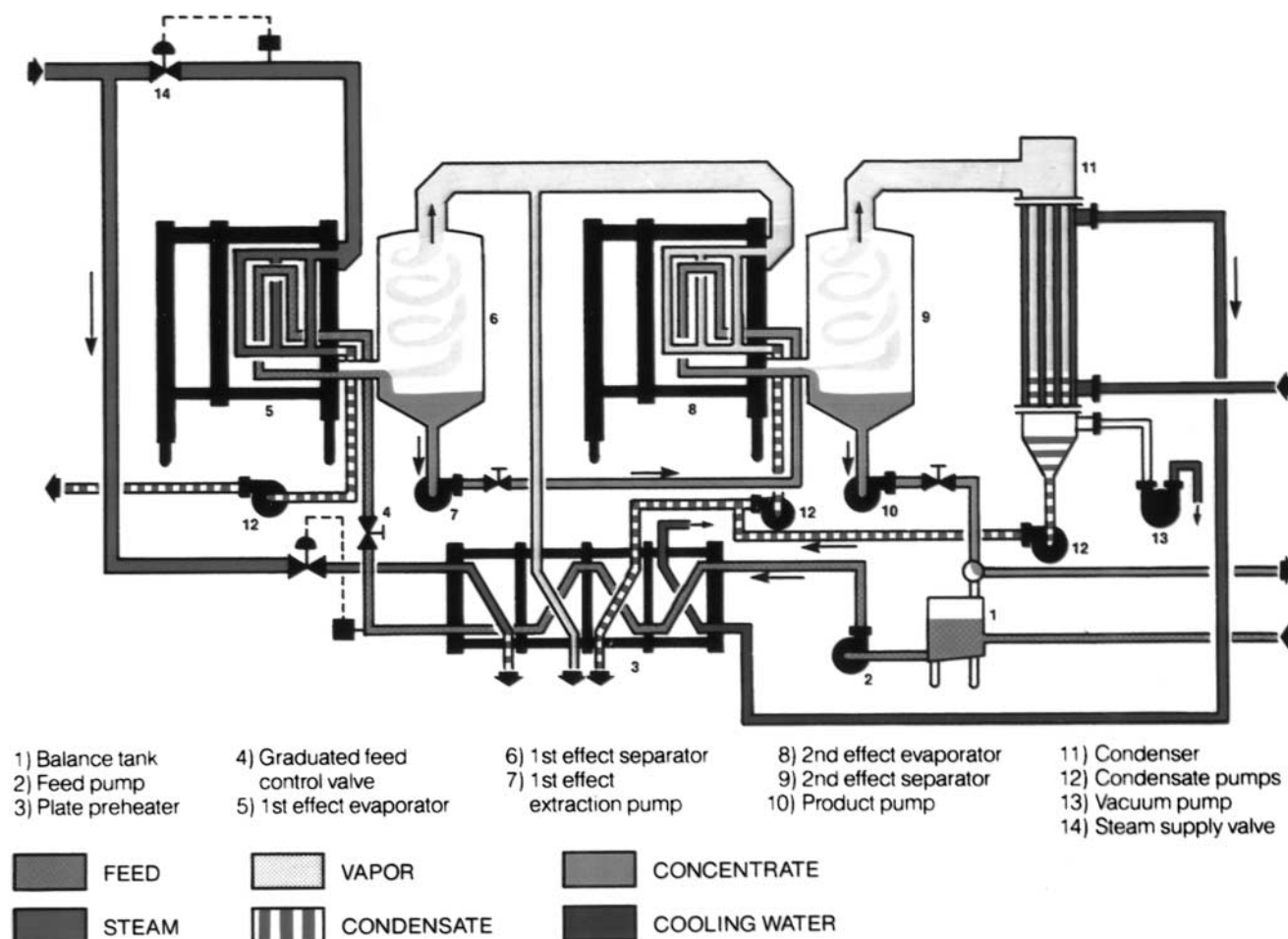


Fig. 3 Two-effect rising/falling film plate evaporator flowsheet. (Courtesy of APV Crepaco, Inc., APV Americas, Rosemont, IL—An Invensys Company.)

A way to estimate vapor enthalpy and data on the internal energy of the liquor as a function of concentration is required.

Even though both the enthalpy and rate of the overhead vapor are often quite constant in time (except for the small sensible thermal energy contribution from the boiling point rise), the rate of heat addition may vary with time because of changes in the overall heat transfer coefficient from surface changes (see below) and because of significant changes in the temperature difference between the liquor and heating medium induced by the boiling point rise. A simple example calculation of batch evaporation can be found in reference (14). The equations involved are similar to those that govern batch distillation.

Many evaporators are operated at substantially steady-state conditions (although heat transfer coefficients will vary slowly with time because of surface changes from scaling, deposition, etc., as noted above). The design of an

evaporator for steady-state operation typically is initiated from the specification of the mass flow rate of material to be processed and its required change in concentration. This information is used in mass balances, which proceed via an energy balance to yield the required rate of heat transfer.

For an evaporator system which has a liquid feed, overhead vapor, and bottoms liquid product, and is used to concentrate species A:

Total mass balance

$$\dot{W}^{(\text{feed})} = \dot{W}^{(\text{overhead vapor})} + \dot{W}^{(\text{bottoms liquid})} \quad (2)$$

Species mass balance

$$\begin{aligned} \dot{W}^{(\text{feed})} x_A^{(\text{feed})} &= \dot{W}^{(\text{overhead vapor})} x_A^{(\text{overhead vapor})} \\ &+ \dot{W}^{(\text{bottoms liquid})} x_A^{(\text{bottoms liquid})} \end{aligned} \quad (3)$$

where

- \dot{W} mass flow rate (total mass/time)
 x mass concentration of species A (mass A/total-mass)

Normally, the feed flow rate and concentration are specified, as are the overhead and bottoms concentrations (the overhead concentration is most often zero). This set of two equations in 2 unknowns can then be solved for the unknown overhead and bottoms mass flow rates.

The required rate of heat transfer can then be calculated from the steady-state energy balance, assuming negligible changes in potential and kinetic energy and no work input (the latter not valid, of course, for vapor recompression evaporators).

$$\dot{Q} = \dot{W}^{(\text{overhead vapor})} \hat{H}^{(\text{overhead vapor})} + \dot{W}^{(\text{bottoms liquid})} \hat{H}^{(\text{bottoms liquid})} - \dot{W}^{(\text{feed})} \hat{H}^{(\text{feed})} \quad (4)$$

where

- \dot{Q} heat transfer rate into system (energy/time)
 \dot{W} flow rate (mass/time)
 \hat{H} enthalpy (energy/mass)

In the above equation, the mass flow rates are known from the mass balance calculation. The enthalpies must be determined from thermodynamic data, which will require specification of the temperature and/or pressure of the stream in combination with the concentrations that were originally specified.

Calculation of the rate of heat transfer required does not of itself determine the heat transfer area required or the configuration thereof. The configuration (tubes, plates, etc.) is typically chosen first, by rules of thumb and experience, depending on the liquor to be processed.

The area is usually calculated, once the configuration is chosen, by using an overall heat transfer coefficient that lumps together all forms of heat transfer in terms of an overall coefficient paired with a characteristic area:

$$\dot{Q} = UAT \quad (5)$$

where

- U overall heat transfer coefficient, valid only when paired with a specified area (energy/time \times length² \times temperature)
 A a specified area normal to heat flow; (e.g., the outside area of the tubes or the inside area of the tubes (length²),
 ΔT Temperature difference between temperature of heating medium and temperature of the liquor

(usually either freestream or bulk temperatures) (temperature).

The overall heat transfer coefficient depends on the properties and flow pattern of the heating medium, the properties and flow pattern of the liquor, the properties of the solid surface that separates the medium and the liquor, and the properties of any deposits at the interface on either side of the separating surface.

In general, heat can be transferred by the three mechanisms of conduction, convection, and radiation (20). In evaporators, the mechanisms of importance are usually convection in the liquor and medium, and conduction through the solid separating them.

In order to calculate the overall heat transfer coefficient in the equation above, the heat transfer properties of the heating medium and the liquor are described in terms of individual heat transfer coefficients, and the heat transfer properties of the separating solid in terms of its thermal conductivity. Deposits at the interface, which one might expect to be described by a thermal conductivity, are usually described instead in terms of either a fouling (heat transfer) coefficient or a "fouling factor" (which is usually defined to have a value of 1000/[fouling coefficient]).

Individual heat transfer coefficients for convection are defined by the equation:

$$\dot{Q} = hAT \quad (6)$$

where

- h individual heat transfer coefficient (energy/time \times length² \times temperature),
 A a characteristic area normal to the flow of heat: typically, the area of the unfouled surface initially in contact with the fluid. In cases where area varies along the heat transfer path, (e.g., tubes), it is necessary to specify on which area the coefficient is based, such as, inside, outside (length²),
 ΔT a specified temperature difference, usually the difference between either the freestream or the bulk temperature and the temperature at the surface.

The rate of heat transfer by conduction can be written in terms of the thermal conductivity:

$$\dot{Q} = kA_{\text{avg}}Tx \quad (7)$$

where

- k thermal conductivity of solid (energy/time \times length \times temperature),
 A_{avg} average area through which heat transfer occurs, e.g., logarithmic mean area for concentric cylinders (length²),

- ΔT temperature drop from one outside surface of the solid to the other outside surface (temperature)
 Δx thickness of solid normal to heat flow (length)

One can relate the overall heat transfer coefficient to the individual steps:

$$\frac{1}{U_{ov}A_{ov}} = \frac{1}{h_{medium}A_{medium}} + \frac{1}{h_{fouling,medium}A_{fouling,medium}} + \frac{x}{kA_{avg,solid}} + \frac{1}{h_{fouling,liquor}A_{fouling,liquor}} + \frac{1}{h_{liquor}A_{liquor}} \quad (8)$$

The overall heat transfer coefficient can be calculated by evaluation of the individual terms in the above equation. Knowledge of the overall temperature drop then permits calculation of the required area. A detailed development of the above is available (5).

The individual heat transfer coefficients for the medium and the liquor can be calculated from general correlations using the properties of the fluid and the velocity fields in the system (20–25). Additional information can be found in the continuing series of the American Society of Mechanical Engineers (26). Detailed studies and bibliographies on prediction of individual heat transfer coefficients for evaporating films on/in horizontal/vertical tubes, can be found in other publications (21, 22, 24–27).

The limiting step in heat transfer is usually the thermal resistance from the liquor itself and/or deposit formation on the liquor side (the last two terms in the previous equation.) On the heating medium side, the heat transfer coefficients are usually for condensation and are therefore substantially larger than those on the liquor side, which are for boiling. The conduction resistance of the tube wall is usually small (but this is not necessarily true of the resistance of deposits that accumulate on the tube wall).

Deposits typically accumulate more on the boiling side than the condensing side. To determine coefficients for systems with substantial surface deposition, experimental data on that particular system is usually necessary.

Heat-sensitive products can break down to insoluble forms that deposit on the surface and inhibit heat transfer. For example, some soluble proteins, when heated, convert to an insoluble form (18). Change in the heat transfer characteristics of the tube surface can also be induced by corrosion.

The liquor can be on either the inside or the outside of the tubes, depending on the physical and chemical characteristics of the materials involved. Considerations include convenience in cleaning deposits from the heat transfer surface, the heat transfer characteristics of the fluids involved, and fluid velocities required for efficient heat transfer or prevention of scale deposition.

A useful table of criteria and data for the rapid design and selection of evaporators is available (10).

Natural circulation evaporators have overall coefficients of the order of $1.1\text{--}3.4 \text{ kW}/(\text{m}^2\text{K}) = 200\text{--}600 \text{ Btu}/(\text{h ft}^2\text{F})$. Adding forced circulation may raise this to the order of $11 \text{ kW}/(\text{m}^2\text{K}) = 2000 \text{ Btu}/(\text{h ft}^2\text{F})$. In agitated-film units, for Newtonian liquids with viscosity of the order of water, coefficients of the order of $2.3 \text{ kW}/(\text{m}^2\text{K}) = 400 \text{ Btu}/(\text{h ft}^2\text{F})$ may be obtained. As the viscosity increases to $10 \text{ Newton sec}/\text{m}^2 = 10,000 \text{ centiPoise}$, the coefficient will drop to the order of $0.7 \text{ kW}/(\text{m}^2\text{K}) = 120 \text{ Btu}/(\text{h ft}^2\text{F})$. More extensive listings of overall coefficients for evaporators may be found in the literature (1, 8, 10, 28).

The heating medium must be at a higher temperature than the liquor, and the resultant temperature driving force must be sufficiently large that excessive area for transfer is not required. One means of increasing the temperature driving force for a heating medium at a given temperature is to reduce the pressure of the liquor side to decrease the boiling temperature. This is a common device in evaporation, and is often accomplished with a steam-jet ejector. Design (and cost) of such ejectors is detailed in the literature (29).

If the overhead vapor is water and the heating medium is steam, the vapor generated is usually comparable in amount and quality to the heating steam used, but is at a lower pressure because the heating steam must be at a higher temperature (therefore, pressure) than the liquor in order to furnish an adequate temperature driving force for heat transfer. A logical question is whether or not to attempt to recover the latent heat in the vapor generated.

The condensing temperature of the vapor does not usually furnish an appropriate temperature difference to permit transferring heat to the liquor (except, perhaps, a small part to sensible heat of the incoming liquor). However, compressing the vapor will raise both its temperature and its condensing temperature, permitting the vapor to be used to transfer its heat of vaporization/condensation to the liquor with consequent recovery of thermal energy.

Unfortunately, the work required for such compression is high-quality (and therefore, expensive) mechanical energy that ends up as low-quality thermal energy. Either thermocompression or mechanical compression may supply the required mechanical energy. Thermocompres-

sion is accomplished by means of high-pressure steam in an ejector system [for design and cost of ejectors see (29)], while mechanical compression is usually done by a centrifugal compressor (1).

An alternative scheme is to split the evaporation process into stages (in different vessels), commonly referred to as *effects*, where the flow of liquor may be in the same direction, the backward direction, or normal to the flow of vapor (1, 9). In such a scheme, the vapor generated in a given effect is used to boil the liquid in a different effect where a proper temperature driving force exists. In multiple-effect evaporation, one exchanges savings in steam costs for increased capital investment in equipment.

Pennink (30) notes that the optimum is usually 3 or 4 effects in a 50,000 lb/h system and 7 to 8 effects in very large systems. Ramakrishna (31) details a shortcut method to estimate the optimum number of effects for multi-effect evaporation, and Ulrich (10) gives a shortcut algorithm for the design of multiple-effect evaporators. A sample calculation can be found in Schilt (15). Cole (18) gives specific steam consumption and minimum evaporation rates for single and multiple-effect evaporators with and without steam-jet thermocompression, as well as data on mechanical vapor recompression cost per ton of water evaporated.

For those who wish to pursue more detailed design, a good starting point for mechanical design of heat exchange equipment is Azbel (9), who also discusses alternative materials of construction. For general discussion of evaporation as well as insight into safety/environmental considerations, see a report from the U.S. Environmental Protection Agency (32). This document discusses failure analysis as applied to evaporators for treatment of effluent from the metal finishing industry. Other useful references, which have extensive bibliographies, are Rubin et al. (33), Knudsen et al. (34), Chisholm (35), and Taborek et al. (36). The continuing series from the American Society of Mechanical Engineers, as exemplified by Shah (37), contains additional information.

COSTS ASSOCIATED WITH EVAPORATORS

The two major costs associated with evaporators, as with any process equipment, are capital investment and operating costs. The best estimate of the installed cost of evaporation systems is, of course, a firm bid from a vendor. The installed cost, however, can be estimated based on the heat transfer surface area, as in Peters and Timmerhaus (38). Costs taken from published references

must be adjusted for changes subsequent to the time of publication. To do this, one may use an index such as the Marshall and Swift all-industry index. The value of this index is published each month in *Chemical Engineering*, a McGraw-Hill publication. Further information on the use of this and other cost indices as well as their histories are available, for example, in Peters and Timmerhaus (38) and Ulrich (10). Variation of purchased evaporator costs with material of construction and pressure can also be found in Ulrich (10).

A chart to estimate the costs of ejectors for thermocompression has been developed (29). Approximate costs of compressors for mechanical vapor recompression also can be found (38–40). In addition, these publications contain details of cost estimation for heat exchangers. For more detailed estimation of cost of shell-and-tube exchangers, see Purohit (41–43). Plate-and-frame and spiral-plate heat exchanger costs can be estimated using Kumana (44).

Operating expenses can be approximated using published techniques (10, 38). These are mainly useful for preliminary cost estimates only. Such items as raw materials, operating labor, utilities, supervisory expenses, maintenance and repairs, etc., may vary greatly depending on the specific process in question.

OPERATION AND CONTROL OF EVAPORATORS

Many of the problems in operation and control of a given evaporator system will be specific to the application. However, all systems need to answer such questions as how to evaluate performance, how best to schedule periodic *boil outs* (cleaning), how to measure and control variables typified by temperature, pressure, fluid level, fluid flow rate, composition, etc., and how to detect faults in evaporator operation quickly and efficiently (45, 46).

At one time, the American Institute of Chemical Engineers issued a guide to performance testing of evaporators (47). The Instrument Society of America issues a book-length guide for the operation and control of evaporators (2), which covers, among other topics, such operational considerations as the optimum use of boil outs. Instrumentation is covered in detail, including variables, the choice of measurement and measurement method, and both design and implementation of the control system including digital techniques. This work contains both chapter bibliographies and a general bibliography.

Operation of an evaporator for minimum cost of production involves scheduling cleaning cycles to remove scale or deposits. Minimizing costs requires the balancing of increased evaporation rate against out-of-service time. Shutdown involves costs associated not only with cleaning, but emptying and refilling as well. The crux of such optimization is the function used to describe the evolution of scale formation with time.

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